Capabilities of fuel cell micro-CHPs in a smart grid perspective

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Executive summary

Fuel cell (FC) micro combined heat and power (micro-CHP) is a distributed generation technology which can help stabilise the electricity grid. The FC micro-CHP technology promises to support the grid by compensating production fluctuations of intermittent electricity production. FC micro-CHPs have the potential of being an attractive technology in a market where flexibility is of increased importance.

As the European electricity mix moves towards a higher share of intermittently generated electricity, the generated energy will to a lessening extend correspond to patterns of consumption. Pressure on balancing supply and demand may also be enlarged by increasing peak demand, as electric vehicles and electric heating become more prevalent. This creates a necessity for technologies which can help compensate for the induced electricity fluctuations. At the EU level, policymakers recognise that our current energy system will need to adapt to this new context. As part of the Energy Union framework strategy[1], the European Commission has launched a process to rethink the present assumptions governing our energy markets and allow for the transition from highly centralised to more decentralised generation. It is expected that this will give new market players the opportunity to play a greater role in the energy system in areas such as flexible generation, demand response, renewables and as energy service providers[2]. The findings presented in this paper contribute to this discussion by highlighting the potential of FC-based micro-CHP in addressing some of the challenges of the future energy systems, through enabling technologies like smart grids and energy storage.

A systems approach must be taken when evaluating FC micro-CHP technologies, looking at the potential of this technology in the framework of the smart grid development. Grid stabilisation and distributed generation require a smart grid to be as effective as possible. A smart grid is a grid where information and communication technology is used to coordinate generation and distribution and ensure high degrees of interactions between generation technologies, utilities, consumers and additional stakeholders.

From a technical point of view, FC-based micro-CHP is well equipped for smart grid integration. Systems are typically equipped with the possibility of being remotely operated and controlled. Further FC-based micro-CHP systems can adjust to external heat and power demands at seconds notice when at operation temperature. Other advantages of the technology include that the generation is inherently distributed eschewing transmission losses, that generated power can be sold back to the grid and low to zero emission of CO_2 and NO_x. Finally, fast response time and aggregation capabilities make FC-based micro-CHPs well suited for smart grid controlled distributed generation which can limit transmission losses in the grid.

For FC-micro-CHP to positively contribute to grid stability in the context of the emerging smart grid model, the viability of aggregation of multiple units into a virtual power plant needs to be

[1] European Commission, 25.02.2015. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. Retrieved from: http://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF

[2] European Commission, 15.06.2015. Communication […] Launching the public consultation on a new energy market design. Retrieved from: http://ec.europa.eu/energy/sites/ener/files/documents/1_EN_ACT_part1_v11.pdf

considered. At a capacity of 1 kW per system, an estimated minimum of 1000 units in a virtual power plant is required (1 MW). The rewards for the aggregator and installation owners will need to outweigh the administrative and coordination costs required for such a complex operation in order for the virtual power plant model to gain ground.

FC micro-CHP is a dispatchable technology, which can provide services to the grid in a flexible way, especially when coupled with heat or electricity storage and controls. Yet in certain situations, when the technology is installed in regions where heat is not needed for long period of time as well as in non-residential use where the unit is not in operation over the weekend, the potential of the technology to support the grid is reduced.

It is suggested that utility companies should be able to control the systems. Here, the utility companies would act as operators and aggregators of the micro-CHP systems. Baseline operation of the systems should be a continuous production of a fixed amount of electricity. This should be supplemented with generation profile adjustments based on household and external needs. A generation profile based on the household's average needs could be the basis of such operation.

About this position paper

This position paper is a part of Europe's largest demonstration project for fuel-cell-based micro-CHP (micro combined heat and power) systems, ene.field (*European-wide field trials for residential fuel cell micro-CHP*, grant no. 303462). The aim of the project is to demonstrate small stationary fuel cell systems for residential and commercial applications. The project will deploy up to 1000 micro-CHP units in 12 EU member states. This is a step change in the volume of fuel cell micro-CHP deployment in Europe and an important step to push the technology towards commercialization. The project involves 26 partners. Besides the manufacturers of the FC systems, several research institutes as well as utilities are also involved as partners in the project.

This position paper was written in the framework of the ene.field project. The paper was curated and partly written by the Technical University of Denmark (Carsten Brorson Prag, Jonathan Hallinder and Eva Ravn Nielsen). Input regarding the FC micro-CHP integration (Chapter 2) is based on was provided by Baxi Innotech, Bosch, Ceramic Fuel Cells, Dantherm Power, Elcore, Riesaer Brennstoffzellentechnik, SOLIDpower and Vaillant. Contributions to the discussion of FC micro-CHPs from a utility perspective (Chapter 3) were made by Dong Energy, Dolomiti Energia, GDF-SUEZ and British Gas.

This position paper was written within the framework of the ene.field project.

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Chapter 1: Introduction

1.1 Aim and outline

The aim of this report is to present and discuss the current status of fuel cell (FC) micro combined heat and power (micro-CHP) capabilities in a smart grid perspective. The incorporation of fuel cell micro combined heat and power (CHP) systems into the smart grid will be the specific focus.

The introductory chapter will give an overview on smart grid concepts, a clarification of the need for smart grids as well as an introduction to FC micro-CHPs.

This report presents the collected views of 8 manufacturers on the capabilities of FC micro-CHPs and the challenges with smart grid integration of such systems. A synopsis of these views can be found in Chapter 2 and the full information can be found in Annex A.1.

In Chapter 3 FC micro-CHPs in a smart grid context will be discussed from the point of view of European utilities. This discussion is based on the answers of the manufacturer questionnaires in the previous chapter.

Finally, Chapter 4 will detail conclusions and recommendations on further steps.

1.2 General introduction to smart grids

A smart grid is an extension of the current electrical grid, as seen in Europe or North America. The definition of a smart grid is nebulous because a smart grid is more defined by what it seeks to achieve than how it achieves it. A smart grid is an all-encompassing coordination of the capabilities and needs of generators, grid operators and end-users. As any grid it seeks to stabilise the delivery of electricity. Additionally, it aims to achieve a higher utilisation of resources compared to traditional grids using advanced technologies. This can be achieved in a number of ways and with a host of tools depending on the situation, the utilities, the grid managers and the consumers.

Historically, the electricity system has been highly centralised, requiring important investments in long range transmission infrastructure. With the introduction of smart grids, we see the emergence of a trend towards higher decentralisation of the energy system with the following benefits: A smart grid will aid limiting losses in transmission [1] through a constant analysis of the grid [2]. A smart grid can also aid distributed generation by minimising the distance from generation to consumption thus limiting the need for long range transmission at all.

Smart grids will span over all distribution and generation levels ranging from high to low voltage grid, large to small scale production and remote as well as on-site control of decentralised generation [3] (see **Figure 1**).

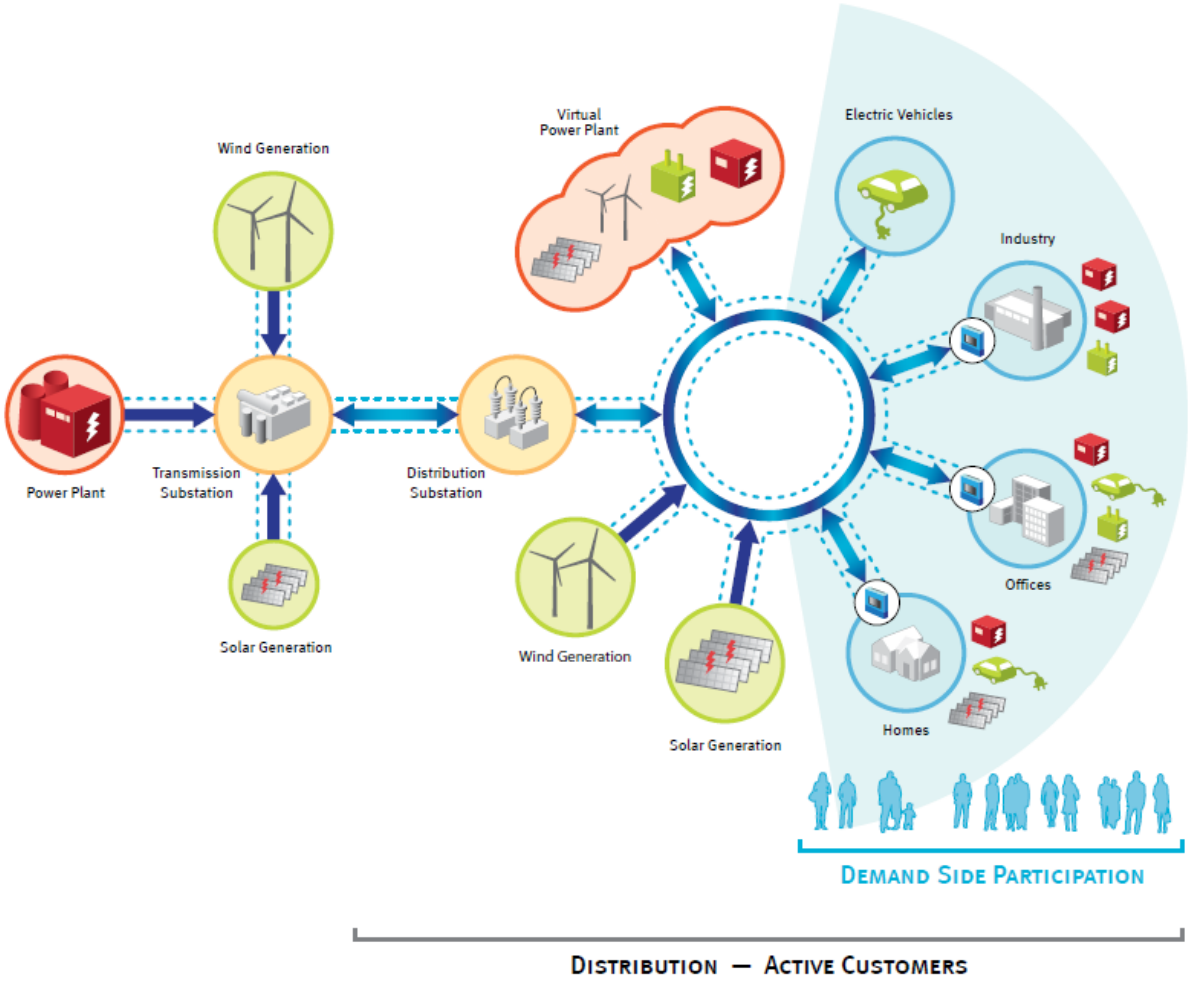

Figure 1: Visual representation of the smart grid. The key concepts are the decentralised generation and the distribution flexibility [4].

1.2.1 Why do we need a smart electricity grid?

Grid balancing, as described above, will become essential with the introduction of larger amounts of intermittent energy sources into the energy mix. Intermitted sources such as wind power and photovoltaic (PV) generation require that other generation system in the grid can quickly and flexibly react to a change of production. As the intermittent renewable sources are fluctuating, other systems will have to be able to start up, resume production, go idle or shut down in reaction to the intermittent electricity generation. While this is all happening in the traditional grid introduction of new technologies, such as heat pumps, electric vehicles, electrolysers and micro-CHPs, will require faster and more intricate communication between all the components connected to the grid.

At times of high energy production from renewable resources, excess energy will be stored in order to be used in times of low energy production from renewable resources. Storages can come in several forms such as: Pumped hydro storage (PHS), compressed air energy storage, batteries, flywheels and gas storage (from electrolysis). All of these have different energy recovery times ranging from seconds to tens of minutes. Coordination of storage of energy over such large quantity

of units and technologies as well as the coordination of utilisation of aforementioned stored energy will require a smart grid.

This kind of coordination will also be needed for the decentralised power generators. As an example remote control of CHP units will to some degree be necessary. By using remote control, power production can be dispatched not only when it is needed locally but when it is needed in a grid perspective. The connection to the smart grid allows for purchase of electricity for energy demanding tasks when the price is low. For example charging of an electric vehicle can be done at night at lower cost.

To make it more attractive to include smaller plants into the grid, for example private PV panels, micro-CHPs or rooftop wind turbines, they must be aggregated into virtual power plants (VPP). Aggregated in a VPP, the smaller plants can respond in unison as one large entity making their use much more convenient. Aggregation enables automation of the control of the units aggregated. The contribution of the individual unit in the aggregate can then be fine-tuned to the needs of the grid operators and the costumers.

Apart from improving the stability of the grid, smart grid technology is envisioned as a means of mitigating the effects of blackouts, whether due to weather phenomena or alternative causes of equipment failure [5]. Corrective actions in the case of grid instability will be similar to the ones used today. Available resources will be directed towards the locations most critical for grid and community resiliency [6]. In the case of areas with a high amount of distributed generation, such a corrective action may be to effectively disconnect a community from the grid and the distributed generation lift the burden. The difference lies in methods for detecting the conditions of the grid and implementation of corrective actions. The two way communication capabilities of smart grid technology gives a cost competitive way of monitoring and implementing such isolation, referred to as islanding [7].

One thing is certain: There is no “silver bullet” technology solution to address the de-carbonisation of the electricity system while still ensuring grid stability in a cost effective way. The future energy supply will most likely be based on several different technologies with a large variety of power output [8]. These technologies will make up a complex mix in the power grid. The preference for these technologies will of course depend on geographical location. Every technology has requirements and advantages which makes them more or less well suited for a specific region, country or terrain.

Wind and solar power are intermittent and will therefore increase the need for grid balancing energy storages. Examples of some production and storage technologies relevant in a smart grid context are given in **Table 1**. Fuel cells are also included as they are tightly linked to energy recovery from hydrogen and synthetic fuel storage. While other recovery technologies exist, fuel cells are among the most efficient and have a low carbon impact.

Table 1: Intermittent electricity production and grid balancing technologies

Intermittent Production Technology	Notes
Wind power	Low environmental impact but intermittent. On track to becoming a defining technology in the energy mixes on several markets.
Solar power (PV)	Low environmental impact but intermittent.

Storage Technology	Reaction time	Notes
Batteries	Seconds	
Electrolysis	Depends on technology. Seconds if at operation temperature.	Mature versions available and commercial products exist. Technologies with improved efficiency under development.
Pumped hydro storage	Few minutes to half an hour depending on operation.	Potentially damaging to wildlife and water quality.

Energy recovery technology		
Fuel cells	Seconds if hot. Start-up time from cold cells depends on technology.	Low environmental impact when running on renewable natural gas and even lower when running on hydrogen. Electrical efficiency reported as high as 60% [9], overall efficiency up to 90% [10] and CO_2 emissions as low as 240 g/kWh [9].

Since various technologies of various power output, response time and fluctuating power production will be part of the energy mix in the future, the current power grid has to be updated to be able to cope with this. Thus, the grid has to become "smarter" and more flexible. The smart grid is a necessity.

More information on smart grids in practice can be found in Annex A.4 in the form of a brief description of selected projects demonstrating smart grid technology.

1.3 Fuel cells and fuel-cell-based micro-CHP systems

1.3.1. Fuel cells

A fuel cell is an electrochemical device that directly converts chemical energy into electricity, heat, water and in some instances CO_2. Typically, fuel cells are fed hydrogen (either through reformation or partial oxidation of fossil fuels such as natural gas, gasoline or diesel or derived from water though electrolysis) or natural gas. At the moment the vast majority of demonstrated fuel cell systems run, directly or indirectly, on natural gas. Due to the capabilities of fuel cells, it is the hope that alternatives with low environmental impact, such as hydrogen from water electrolysis, will supplant fossil hydrogen sources further down the line. This prospect promises a way of generating electricity and heat with very low CO_2 impact and no NO_x formation [11].

There are several types of fuel cells which are traditionally named after the electrolyte material used in the cells. The most common types are polymer electrolyte membrane (PEM) fuel cell and solid oxide fuel cells (SOFC). **Figure 2** shows the operating principle for a solid oxide fuel cell.

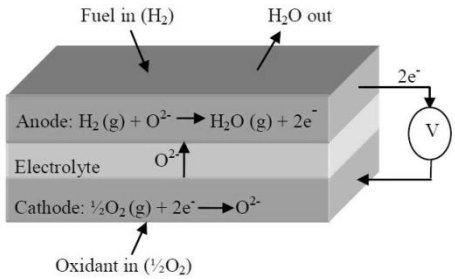

Figure 2. Working principle of an SOFC including electrode reactions, using hydrogen as the fuel.

Most fuel cells are operated above room temperature. A fuel cell at the operation temperature is referred to as "hot", and a fuel cell which is not at operation temperature is referred to as "cold". This is especially relevant when discussing fuel cells in stand-by mode where no current is drawn and the cell is kept at operation temperature. As the cell is still hot, it can be brought back into operation very quickly compared to a cold cell which has heat up before being ready for operation.

To make a whole system, several fuel cells are combined into a stack which is combined with a large number of external components and help systems such as reformer, inverters, water supply, etc.

1.3.2. Fuel-cell-based micro-CHP systems

Micro combined heat and power (micro-CHP) systems are co-generation systems. That is to say they produce both electricity and heat. According to the European definition, a micro-CHP system has a maximum electric power output of 50 kW [12]. The electrical efficiency of a fuel-cell-based micro-CHP system has been reported as high as 60% [9], total efficiency up to 90% [10] and CO_2 emissions as low as 240 g/kWh [9]. This is comparable to modern combined cycle power plants [13]. The possibility of a high utilization of the produced heat is a big advantage for fuel-cell-based micro-CHP technology. Micro-CHP systems can be used in buildings off the grid for primary heat and power generation as well as in buildings connected to the grid allowing for the export of excess produced electricity at a profit. Such distributed electricity generation can, as mentioned, potentially increase the power supply security in a future electricity grid when electricity generation from intermittent renewable energy technologies is lacking due to absence of wind or sun.

A micro-CHP unit needs to be connected to the gas grid (or a separate gas supply such as bottle gas) to fuel the fuel cell. An electricity grid connection is an additional requirement if export of excess electricity and import electricity when there is a production deficit is desired. **Figure 3** shows a sketch of a micro-CHP unit installed in a residential house.

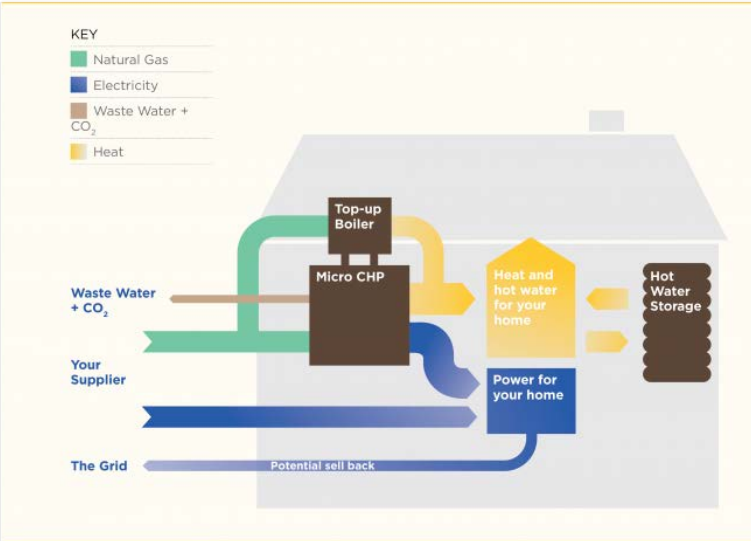

Figure 3. Sketch showing a micro-CHP installed in a residential house [14].

More information on FC micro-CHPs in practice in the form of a brief overview of some of the projects in the field can be found in Annex A.3.

Chapter 2: Fuel-cell-based micro-CHP systems: the role in a future smart grid

Summary of chapter 2

The capabilities FC micro-CHPs are well suited to play an important role in the future of an intermittent energy mix. As the power output of the individual system is small, aggregation of systems into virtual power plants is both necessary and possible. This capability exists and has previously been demonstrated. Aggregation can take advantage of the comparatively fast response time of the FC systems. Decentralised generation afforded by micro-CHPs installed at the point of consumption can limit power transmission losses. Multiple operation modes, are possible and base load operation with the possibility of adjustment based on consumer- and grid needs is suggested.

This chapter presents the collected views of 8 manufacturers on the capabilities of FC micro-CHPs and challenges with grid integration of such systems. The views of the manufacturers were collected through a questionnaire. In this chapter, the views will be presented as a highly abridged synopsis. The full questions and answers can be found in Annex A.1. This Annex gives a great overview of the current capabilities and future prospects of FC micro-CHP technology and is highly recommended reading.

The information presented in this chapter was used as a basis for the discussion on FC micro-CHP grid integration found in Chapter 3. That discussion was conducted from the point of view of the utilities companies.

2.1 Manufacturers views on the capabilities of FC micro-CHPs.

Fuel cell micro-CHP systems are one piece of the puzzle that is our future energy grid.
A more intermittent energy mix will require stabilisation and thus there will be a need for technologies which can help with this task. The on-site generation from FC micro-CHPs can contribute to the grid stabilisation at hours of low energy generation from the intermittent sources. Similarly, at times of energy surplus, a FC micro-CHP can be allowed to go idle. This makes the FC micro-CHPs compatible with intermittent generation, a desirable trade as balancing the grid in the presence of intermittent generation is expected to be a substantial challenge in years to come.

As the output power of a single FC micro-CHP system is low, larger clusters, or virtual power plants, are required to make their use practical. Here, combined control or aggregation is used to coordinate the output of a large amount of systems. This requires remote active control of the systems to synchronise the distributed generation of the FC micro-CHPs. This capability is already proven in manufactured systems.
The aggregator is needed to reach market bid volumes and to pool systems with other generators. Such control could be in the hands of utilities or grid operators and requires operation control of the FC micro-CHP systems. For running such aggregated virtual power plants, it is necessary that the grid operator knows what the current power output from the micro-CHP units is. It is also necessary that

the grid operator has the ability to take control of the micro-CHP systems connected to the grid within a pre-established set of conditions.

At operation temperature, FC micro-CHPs can adjust their power output within seconds to suit the needs of the grid balancing and the household. Start-up from cold to operation temperature may require much longer time. This requirement of a constantly hot cell is not considered a large problem as other factors already created incentives for this. To clarify, these are factors such as ensuring constant performance, grid stabilisation predictability, power export subsidies and household needs. It should be noted that while start/stop cycles may reduce performance, varying the output power does not. This is a great advantage as reducing the output power can in most situations substitute complete shut-down of the FC micro-CHP system. Currently, electric energy losses from central generation (traditional power plants) to consumption are in the order of 5-8 %. This is mainly due to transmission losses in power lines. With distributed generation, these types of losses can be reduced since electricity is produced at the site of consumption. The fast response time of FC micro-CHPs together with their aggregation capabilities makes them well suited for smart grid controlled distributed generation.

A FC micro-CHP can be operated in multiple modes. The most relevant are heat load following, electrical load following, grid following and constant load. As heat load following mode results in suboptimal electricity production and suboptimal economics, it is expected that actual operation will be a combination of electrical load following, grid following and constant load.
One possible way of operation could be the following: By default, the systems are providing base load as long as there is no need for grid balancing. This delivers the best internal rate of return to the home owner. More electricity will be produced if there is power shortage and selling price on the grid (Power Spot Exchange, APX) is high. Less power will be produced if there is more than enough power such as during sunny daytime and windy hours.

Chapter 3: Discussion of FC micro-CHPs from a utility perspective

Summary of chapter 3

The technical capabilities for integration of FC micro-CHPs are present and available. Aggregation of systems into virtual power plants is feasible but relies on competitive economics. This includes investments, running costs and the disadvantage of handling systems with individual owners.

The operation of FC micro-CHP systems relies on system up-time, response time, consumer needs and grid needs. Ideal operation would be an electrical load-following mode directed by a tailored profile for the individual household with the additional option of automatic adjustment to the internal and external needs. For the utility company to service the individual system owner, control of electrical and thermal power is a necessity.

Economic subsidies are at the moment necessary. In countries with feed-in tariffs, these are the driving factor. Non-economic barriers and hidden costs play a large role in some markets, while standardisation and clarity would greatly help market development.

In this section FC micro-CHPs will be discussed from a utility point of view. The discussion is based on questions derived from the contributions from the manufacturers. The discussion questions can be found in their entirety in Annex A.2. Under each headline, challenges and issues of FC micro-CHP deployment related to that topic are treated.

Aggregation

Some major assumptions for small scale FCs to reach remarkable future shares of the coming balancing market for power are:

- That aggregation is possible for many small units through a common system that can control many small units and balance outputs.
- Fast response times for each single unit, which mostly will mean that systems have to be at operation temperature.
- Economic competitive solutions

The first point seems to be a realistic future case with the present level for data communication. However, a hidden precondition seems to be one owner for all the small FC units or, in a more difficult case, one “system responsible” with a lot of agreements with all owners of micro-CHPs. The reason for the need of one body to own all the small FC units is the demand for at least 1 MW, maybe 10 MW, from one “body” to have the right to make a bid for the power balance market.
From the manufactures side it has been observed that:

"[…] larger clusters, or virtual power plants, are required for any benefit to be had. Here, combined control or aggregation is used to coordinate the output of a large amount of systems. This requires remote active control of the systems to synchronise the distributed generation of the FC micro-CHPs. This capability is already proven in manufactured systems. This control can be done on the

level of the individual FC micro-CHP in the virtual plant over the internet. Thus complex operations regarding power output are possible, creating a powerful tool for grid optimisation"

Further:

"FC micro-CHPs can adjust their power output within seconds to suit the needs of the grid balancing and the household. This does require the FC micro-CHP to remain hot at all times as start-up from cold to operation temperature may require much longer time. Some systems have reported start-up times from cold to operation temperature in the range of hours".

So the manufacturers believe in a future for this solution. It is technical feasible, but the big question is - will it also be economic feasible? That is the major challenge for the fuel cell industry. If the industry can produce a competitive product, for sure there will be a market.

Ordinarily, the minimum power requested by the responsible for balancing the grid, the transmission system operator (TSO), is in the range of megawatts. If micro-CHPs are to be the base for this power demand, then input from several thousand micro-CHPs will be needed.

It seems realistic to reach the required virtual power plant size from a technical point of view, but it is uncertain whether it will be competitive with existing systems for power balancing.

It is the responsibility of the TSO to balance the local power production and consumption. Utilities can supply the TSO with some commercial back-up units for that purpose. If micro-CHPs should enter this market, the technology must be competitive with e.g. larger CHP systems, heat pumps or central power stations that deliver the same service. The utilities do not want to spend extra money for at power balance they already have today. Should FC micro-CHPs enter this market, the technology must show an economic advantage over conventional technologies.

If the cost of the individual fuel cell was competitive, utilities would test a balancing system based on the sufficient number of FC micro-CHPs.

From the manufacturers' side, it has been said that they are not interested in the ability to control FC micro-CHPs connected to the grid*: "Some of the manufacturers […] are of the opinion that the generation of power of the FC micro-CHPs should be regulated by the utilities".*

This statement seems in line with the different role of utilities and manufacturers of FC, but still the manufacturers have to offer competitive FC micro-CHPs.

Aggregated micro-CHP VPPs will only be of interest for utilities if the system is economic competitive with conventional methods for balancing of power networks. "Economic competitive" covers both investment and running cost for the system as well as all the costs connected to the bureaucracy introduced by the handling of systems with many thousand owners.

Operation

The use of micro-CHP units based on fuel cell technology in a smart grid context, introduces into the operational management (operation mode) a certain number of issues never approached in a normal household.

The need of an aggregation of systems implemented through a full remote control managed by an external operator instead of the single owner of the single system definitely requires the possibility of a real-time exchange of information relevant to the operation condition of the units. All this must be combined with knowledge of the technical characteristics of the unit itself.

From the technical point of view, the operator shall at all times know the available amount of power, as the sum of residual power over the available units. As the TSO determines for each operator a given response time for power delivery, it is important for the operator to know the response time from each unit to meet these requirements. The simplest condition would be to have identical (or very similar) systems within each individual aggregate as this will standardize the response of the aggregated system to the needs of the grid requirements.

When considering the response times of a FC unit to a load variation request, there are two general scenarios to consider:

1) If the response times are in the range of seconds or milliseconds, system operators will function as distributors in terms of the provision of grid services such as regulation of the reactive power, local adjustment of voltage and the reduction of grid congestion.

2) If, on the other hand, the reaction times are measured in minutes, or more, the only kind of operator who could be interested is a "commercial" operator (seller), who may obviate the need for displacement for production programs or for market needs. That is, an operator who only regulates power output based on commercial needs and not on grid technical needs.

Whether from the standard management of the individual end user, or the aggregated system, point of view, the response times of the system to a load change request is a primary characteristic to be taken in account.

While not a necessity, the FC micro-CHP must be operational at all times to obtain most benefits for the utility company. This reduces the attractiveness of the technology in regions where heat is not needed for long periods of time as well as in non-residential use where heat and power is not needed over the weekend.

In many applications, however, at present, the driver is still the heat demand. This is especially true during the summer period (from April to October) when the heat demand is drastically reduced.

As stated above, in order to implement a smart grid function for the FC micro-CHP units, it is fundamental to have the knowledge and the ability to access a potential reserve of energy that can be drawn at the request of the operator. At the same time, the system efficiency must be taken into account (by an efficient use of the generated heat) as must cost of energy, costs of natural gas, and

other economic parameters. These are all different and unique in each country/region and directly affect the operations mode definition.

An ideal solution for the utility companies would be electrical load following mode, such as the one proposed by the manufacturers in the previous chapter, optimized by a well-designed heat storage capacity (based on the total day heat demand with no waste energy), and a daily stepped pre-set load profile based on a “typical” energy need profile of the end user. This profile should then automatically be adjusted according to the demand over time or manually by the “network operator” via remote control for grid balancing needs.

These grid needs can obviously be in contrast with the householder needs; compensation criteria of costs and remuneration for the householder shall be definitely defined in order to move the investment and operation costs (at least partially) from the householder to the "grid operator".

Data, metering and control

The currently available systems for metering, data collection and system control are in themselves sufficiently advanced to fill their required roll in a future integration of FC micro-CHPs in a smart grid. The response time of the FC micro-CHPs may however pose a limitation to the practical use of these metering and control systems.

As these systems for metering, data collection and system control operate via the internet, data security will ultimately be of high importance. At the current stage of implementation, this is however of little concern and has not been given a lot of attention. This is considered an important next step in the implementation and further development of FC micro-CHP systems.

If a utility company is to serve the individual customer via incorporation of FC micro-CHPs, they must be able to control the output of the installed unit. The utility company must be able to control either the electrical or the thermal power output of the units as a minimum. If the micro-CHPs are to be used in a smart grid context, it must be possible to control the electrical power output specifically.

Economics

The deployment and economics of FC micro-CHPs are still very much subsidy driven. The most commonly seen subsidy mechanism, or incentive, is the feed-in tariff (FiT) regime.

In countries where FiT are available, such as Great Britain, FiTs are at around the correct level. While any increase would be much welcomed, ultimately it is the consumer who will pay for these increases. FiTs are paid based on fed-in electricity which is in turn dependent on excess generation. The better the product fits its application, the more it will run and the more excess electricity will be generated to earn more (FiTs).

It should be noted that at this moment some countries, e.g. Italy, have no direct subsidies for FC micro-CHPs. However, the condition of "high efficiency cogeneration" (high level of global coefficient of performance) must be maintained for tax and environmental reasons.

In countries where no FiTs are available, it is possible that the cost of purchase and installation of the micro-CHP unit becomes insurmountable for the consumer. Whichever benefits there may be in installing a FC micro-CHP are overshadowed by the initial expenditure. In these countries without FiTs some expenses may not be apparent from the onset as paperwork and bureaucratic processes may also result in obfuscated costs. This alienates the consumer, not only to the system but to the product as well.

Distributed generation

As mentioned in the previous chapter, a reduction of transmission losses will be afforded by the in-house generation promised by technologies such as FC micro-CHPs. To make a difference in practice micro-CHP installation volumes must be in the order of several thousands. The grid capacity will in practice be increased as grid electricity demand will be reduced by the distributed generation. That is to say, the existing power loss of 5-7% from power station to consumer will be minimised through the local micro-CHP power production.

Limiting factors and challenges

The greatest limiting factor, as seen from a utility perspective, to the introduction of FC micro-CHPs to the market in a broad sense, is the cost of the units. The reliance on subsidies is pervasive and will continue until large enough manufacturing numbers are met.

Additional important issues include the size and weight of the units and regionally specific challenges such as bureaucracy and no easy way of installing the FC micro-CHPs. In the United Kingdom FC micro-CHPs cannot at this point in time be integrated into UK systems in a simple manner. The typical UK home uses a radiator type system operating at higher flow and return temperatures than the FC system does and this is borne out as there is limited space for buffer tanks or plant rooms. Thus the product is not easy to install and where it is possible, due to the balance of system required, it can be a costly appliance to install. Hence, product manufacturers need to continue to develop the FCs to suit the mass market which will inevitably drive volume costs down and increase the market.

Chapter 4: Conclusions and future steps

FC micro-CHPs are an interesting option for balancing and aligning the grid for renewable energy sources. The technology promises assistance in the compensation of the fluctuations caused by intermittent energy sources and has the potential of being an attractive technology with low environmental impact. The capacity to function in aggregates where each FC micro-CHP unit is controlled individually and remotely has already been demonstrated in commercial systems. An additional advantage is that a FC micro-CHP at operation temperature can adjust its power output within seconds to quickly fit either grid balancing needs or the needs of the household where it is installed.

The technology does however face challenges. Product cost is a general challenge of micro-CHPs. Establishing the right framework for FC micro-CHPs to contribute to the grid, through a system of rewards combined with innovative business models, may actually help relieve the high up-front costs. This also should be viewed in the context of de-carbonisation and against the costs of extending the grid, as balancing needs will have to be increasingly met by low carbon technologies. Therefore, the question becomes what is the cheapest, low carbon, dispachable source of electricity?

The promise of grid stabilisation through aggregation of fuel cell micro-CHPs is enticing. To realise the potential, this technology depends both on bringing the unit costs down as well as on putting in place a framework that creates a market for balancing and other ancillary services. Such a framework should attract new players and new business models that can help to facilitate the process. Aggregators are expected to step in, once the market offers greater rewards for flexible generation and appropriate contractual arrangements can be made to ensure that both the unit owners and aggregators draw benefits from such an arrangement.

While not a necessity, the FC micro-CHP must be operational at all times to obtain most benefits for the utility company. This reduces the attractiveness of the technology in regions where heat is not needed for long periods of time as well as in non-residential use where heat and power is not needed over the weekend.

It is recommended that the FC micro-CHPs are in general operated in an electrical load following mode with a well-designed heat storage capacity. A load profile based on a typical energy need should be applied and adjusted automatically according to demand or grid balancing need. The resources for such operation are available and are in themselves not a limiting factor.

Annexes

A.1 Manufacturer questionnaire and collected responses

In this Annex the full questionnaire posed to the manufacturers can be found together with the unabridged answers to said questionnaire. The questionnaire is first presented in its entirety. Then the combined answers from the manufacturers to the individual questions are presented.

Questionnaire

To investigate the role of fuel-cell-based micro-CHP systems in a smart grid context a questionnaire consisting of 7 questions was distributed to all manufacturers involved in the ene.field project. The questions concerned the capabilities of their technology as well as their perspective on the role of fuel-cell-based micro-CHP systems in a smart grid context. The questions were developed by DTU and the utility partners in the ene.field project. Summaries of the collected responses are presented in the following sub-sections. The distributed questionnaire is presented below:

1) How do you see your micro-CHP systems to contribute to the future energy grid from a smart grid / active control perspective? (capabilities, pros and cons)
2) Which of the following "modes" do you regard as the most relevant for FC-based micro-CHP systems: (please motivate pros and cons for each alternative and you "favourite" mode)
   a. *Heat load following (e.g. follow the heat need of the household, as much as possible)*
   b. *Electrical load following (e.g. follow the electricity need in the household)*
   c. *Grid following (e.g. deliver excess electricity to the grid whenever the grid require)*
   d. *Constant load (e.g. run on a constant load and deliver excess electricity to the grid)*
   e. *Other:*
3) Do you think that the utility or the micro-CHP manufacturer shall have the ability to control the output from the unit? E.g. that the utility can increase the electricity production (remote control) when the grid require more electricity? If yes: how do you think this shall be regulated / controlled?
4) What are the limitations and / or restrictions for FC-based micro-CHP systems in the future smart grids? (That you can think of at the present state)?
5) Can you think of (and motivate) any benefits of FC-based micro-CHPs systems over other small scale electricity producing units (in a smart grid perspective)?
6) Are there any places where you see a greater/smaller potential for FC-based micro-CHP units in the future electricity grid? (geographical and other..)
7) Any other comments and thoughts, for example: parameters that is extra important (response time, remote control, economy (export economy), heat storage etc…)

Questionnaire responses

Question 1: Micro-CHP contributions to the smart gird

Full question: How do you see your fuel cell micro-CHP systems to contribute to the future energy grid from a smart grid / active control perspective? (capabilities, pros and cons…)

Fuel cell (FC) micro-CHP systems are one piece of the puzzle that is our future energy grid.
A more intermittent energy mix will require stabilisation and thus there will be a need for technologies which can help with this task. The on-site generation of FC micro-CHPs can contribute to the grid stabilisation at hours of low energy generation from the intermittent sources. Similarly, at times of energy abundance, a FC micro-CHP can be allowed to go idle and cheap energy may be bought off the grid. This makes the FC micro-CHPs compatible with intermittent generation, a desirable trade as balancing the grid in the presence of intermittent generation is expected to be a substantial challenge in years to come.

As the output power of one FC micro-CHP system is too low to help to stabilise the grid in any meaningful way, larger clusters, or virtual power plants, are required for any benefit to be had. Here, combined control or aggregation is used to coordinate the output of a large amount of systems. This requires remote active control of the systems to synchronise the distributed generation of the FC micro-CHPs. This capability is already proven in manufactured systems. This control can be done on the level of the individual FC micro-CHP in the virtual plant over the internet. Thus complex operations regarding power output are possible, creating a powerful tool for grid optimisation. This fast and intelligent adjustment of energy production is an important feature that sets FC micro-CHPs apart from competing technologies.

FC micro-CHPs can adjust their power output within seconds to suit the needs of the grid balancing and the household. This does require the FC micro-CHP to remain hot at all times, as start-up from cold to operation temperature may require much longer time. Some systems have reported start-up times from cold to operation temperature in the range of hours. As factors such as ensuring constant performance, grid stabilisation predictability, power export subsidies and household need response creates incentives for 24/7 operation, this not a large road block.

Currently, energy losses from central generation to consumption are in the order of 5-8 %. This is mostly due to transmission losses in power lines. With the distributed generation afforded by FC micro-CHPs, these types of losses can be mitigated. The energy is produced where it is needed and spent where it is produced. Thus, the use of the generated power is more efficient.

Power consumption is predicted to increase, even as electric efficiency of appliances increases. This will make increased generation of power a necessity. If this was to be done centrally, an expansion of the power lines would be required as well as an expansion of the central generation power. With distributed generation this expansion can be limited or eliminated as most necessary energy is

generated on-site or locally, thus making central generation unnecessary and circumventing transmission.

While FC micro-CHPs have previously been limited in power generation by their heat generation, this is changing. Power to heat ratios are reported as high at 3 to 1. At these rations power production can be as high as 60% even without the use of waste heat. Electric efficiencies are high over the entire generation range. Manufacturers report e.g. 40 % to 57 % from 500 W to 2000 W.
These generation capacities and outputs make the systems ideal for resident housing and small business use. This is only expected to improve with future generations of systems. Lower waste heat production will also make the systems more reliable from a grid point of view as they can keep a high base load electric generation without having to shed generated heat.

The introduction of this technology means a few challenges must be met.
First of all for financial efficiency, a 24 hour base load operation is necessary. For other operation strategies to be interesting for the owner, compensation or subsidies would be needed.

Constant performance is secured by constant operation. Start/stop cycles reduce performance for all systems. While this is an important challenge, it will in practise be less of a concern as other factors, as stated above, make constant operation desirable.
It should be noted that while start/stop cycles reduce performance, varying the output power does not. This is a great boon as reducing output power can in most situations substitute shutting down the FC micro-CHP system.

Question 2: Favoured operation mode of micro-CHP system

Full question: Which of the following "modes" do you regard as the most relevant for FC-based micro-CHP systems: (please motivate pros and cons for each alternative and you "favourite" mode)

- **Heat load following (e.g. follow the heat need of the household, as much as possible)**
- **Electrical load following (e.g. follow the electricity need in the household)**
- **Grid following (e.g. deliver excess electricity to the grid whenever the grid require)**
- **Constant load (e.g. run on a constant load and deliver excess electricity to the grid)**
- **Other:**

The benefits and drawbacks of the different operation modes will first be presented for each operation mode individually. After this presentation all of the modes will be discussed and compared.

Heat load following:

Heat demand following is the simplest mode of operation. It ensures optimal usage of produced heat, optimal overall efficiency and optimal primary energy- and CO_2 balance. It can be said to be a necessity for having real combined heat and power and makes for an easy concept if only one operation point is used.

It does however result in suboptimal electricity production and suboptimal economics. It is worth noting that because of renovations and new-build homes, heat demand will decrease drastically, whereas power demand will increase. Especially, in homes where heat-pumps provide space-heating and homes where electrical cars will be charged. Therefore, heat-led technologies are to be expected to become more and more unfavourable in the near future.

Electrical load following:

Electrically led technologies can be integrated into and play a major role in smart grids, virtual power plants, demands side management, grid balancing and other next generation technology that needs electrical controlling. This is the best mode for financial efficiency and sensible for small users. It has optimal electricity production as it follows consumption.

This operation mode is complicated however, because of varying operation modes that leads to higher costs for the micro-CHP system. Following the consumer load will also lead to a need for discharge of heat that cannot be used or stored. This will happen when no more heat can be stored in the hot water tank accompanying the FC micro-CHP and will lead to a reduced overall efficiency. Matching electricity house demand will also require extra metering of net export, or estimation of house demand.

Grid following:

Grid following is interesting as it provides a grid service. If FC micro-CHPs are to be used for grid balancing, the system must be able to follow the grids requirements.

Grid following requires integration to the transmission systems operator's (TSO) control centre or frequency-based response depending on electricity balancing mode. Earnings for this service are

expected to be low, as following the requirements of the grid is making generation economically suboptimal. This could however be interesting in a financial point of view if there would be subsidies for making this feature available. Energy efficiency wise it will be suboptimal no matter the subsidies and feed-in tariffs.

Constant load:

Constant load will only be of interest if there is a need for maximum generation, either from the household or from the grid. This will seldom be of interest for the grid as this kind of operation is inflexible and runs contra to grid desires. Constant load operation will also only be relevant as long as heat can be utilized and/or if there is still a subsidy, even if heat needs to be discharged without using it. Economically as well as efficiency wise this operation is suboptimal.

Discussion:

It is to be expected that actual operation will be a combination of electrical load following, grid following and constant load. Here, constant load will either be maximum load or a lower base load. It will however not be constant in the sense that it will be the only applied load. It will be a base load to which the system will return when not following the household load or grid load. Should the household need more hot water than what is available as a consequence of operation, a peak heat boiler may cover this demand.

The three above mentioned different options are all passable but must be evaluated case by case depending on external factors such as the local costs of the energy (electricity costs and gas costs), the user consumptions, the service of net metering, intermittent energy availability, season, and additional economic factors. Essentially, it is a matter of optimizing system earnings which requires both heat and electricity to be utilized.

In general the most relevant mode would be electrical load following mode. This is however naturally limited or capped by the heat demand of the house and the hot water tank capacity available in the residence. Electrical load following is generally the most ecologic and economic way of operation. To fully follow the spontaneous electrical demand of the end user, the dynamics and the output of the FC micro-CHP systems will not be sufficient. It is therefore necessary to allow for grid following and following defined daily load profiles. The owners of the micro-CHP units know best their own daily routines and will be able to show a certain energy sensitivity. So a certain adjustment of their energetical behaviour in line with the load profiles can be expected. This will optimise the use of the “self-made“ electricity.

One possible way of operation could be the following: As a standard, providing a base load when there is no need for power balancing. This delivers the best internal rate of return to the home-owner. More electricity will be produce if there is power shortage, selling price on the grid (power exchange) is high, and it will produce less power if there is more than enough power such as during sunny daytime and windy hours.

In general it is our opinion that a smart grid will choose the best of the above mentioned options based on what is most viable and of highest importance for the local energy community.

Question 3: Remote operation control

Full question: Do you think that the utility or the micro-CHP manufacturer shall have the ability to control the output from the unit? E.g. that the utility can increase the electricity production (remote control) when the grid requires more electricity? If yes: how do you think this shall be regulated / controlled?

Because of more and more volatile renewable energy feed-in, control of the power range is becoming of higher importance for the power industry. Within short-termed plannable energy mixes, fuel cell systems can be reasonably embedded.

It will never be in the interest of a system manufacturer to control a user's FC micro-CHP. Manufacturers focus on producing units with no interest in the actual operation of said systems. As such they should not have any control over their use.

A third entity, an aggregator, is needed to get to market bid volumes and to pool systems with other generators. Such control could be in the hands of utilities or grid operators and requires operation control of the FC micro-CHP systems.
For running such aggregated virtual power plants, it is necessary that the grid operator knows what the current power output from the micro-CHP units is and has the ability to force a net schedule onto the micro-CHP systems connected to the grid.

Regarding the ability for utilities to control FC micro-CHPs connected to the gird, there is no manufacturer consensus. Some of the manufacturers, who were consulted in this position paper, are of the opinion that the generation of power from FC micro-CHPs should be regulated by the utilities. The best following mode is the feed-in-tariff following. This can really contribute to the success of the smart grid. Furthermore, the control of the output power should only be possible if there are many CHPs which can really optimize and stabilize the grid.
Others say that while utility or a service provider should have the ability to control the output of the FC-based micro-CHP unit, the user must always have the ability to override outside control. The devices must have a tamper-evident feature. In addition, the exchanged data should be protected against unauthorized access by third parties.
Again, others are of the opinion that utilities should never have access control functions of a grid connected FC micro-CHP.

The option of grid operator control enables the grid operator to secure its grid balancing and grid controlling power. However, as providing this grid control potentially costs the FC micro-CHP owner money, the owner must always have the final say in this matter. The owner should be able to decide when to sell the power via an aggregator to the grid operator.
If the grid operator has direct and defining access to the unit, the financial compensation has to be regulated.

It may also be gainful if other commercial parties such as new market parties, energy cooperations, (social) housing associations or energy service companies (ESCOs) are able to control the output according to their business models.

Question 4: Restrictions and limitation of micro-CHP systems for smart grid use

Full question: What are the limitations and/or restrictions for FC-based micro-CHP systems in the future smart grids? (That you can think of at the present state)?

The most restricting feature of the FC micro-CHPs is the limited power output of an isolated unit. You need quite a lot of units to have an impact on the grid. Whether integration of micro-CHPs in the smart grid is useful or not, depends on the amount of CHPs in the grid and the cumulated electric power of these micro-CHPs. Thus, a large installation base and intelligent aggregation are needed. The greater the installation base, the greater the impact of the technology, and the greater the gain of the demanding control procedures and the expensive equipment. Even though this is challenging, it is achievable.

If systems are required to run in heat controlled mode this could be a limitation to their integration into the grid. This could be systems that only run during heat demand on winter days or during hot-domestic water preparation a couple of hours a day. Thus, wise use of heat would be necessary.

Other limitations could be the part-load behaviour and thermo-cycle capabilities of the different technologies (fuel cell types). This is of lower importance as next generation FCs ready for deployment have already dealt with these restrictions or limitations.

Question 5: Benefits of micro-CHPs over small scale electricity producing units

Full question: Can you think of (and motivate) any benefits of FC-based micro-CHPs systems over other small-scale electricity producing units (in a smart grid perspective)?

FC-based micro-CHP systems have the best possible electrical efficiency of the available small scale electricity producing units available on the market. Therefore, they have the highest potential in future business cases where heat will play a continually decreasing role.

They provide the base load in single and two-family homes and are able to influence the energy consumption in a smart home installation towards an optimized consumption.

Once larger scale production have been realised it is assumed that FC micro-CHPs will have far less initial and maintenance cost than e.g. engine driven or Stirling-based generators. At the same time, the FC micro-CHPs give little to no noise and vibrations contrary to the aforementioned generators. Far better part-load behaviour of FC micro-CHPs compared to other systems is also a great advantage. The engine driven or Stirling-based generators cannot sensibly be modulated while FCs can. This is quite possibly the greatest advantage the FC micro-CHP has over other technologies.

It is much easier to control FC micro-CHPs over the internet, in smart grids and home power management systems compared to other technologies. The response time is much lower as well. For grid stabilisation purposes, fuel cell technologies also have the advantages of small heat output and high electric efficiency, they are not dependent on wind and sunlight contrary to renewable generators and their constant availability ensures reliability for the grid operators needs for power.
Lastly, the low CO_2 emissions and no NO_x emissions make the technology green and attractive. This is of interest for both the owner and the aggregator as it gives a green image.

FC being a DC source might give some flexibility over reciprocating generators with regards to power quality improvement active control. This does however impose requirement on power electronics though.

FC micro-CHPs can produce electricity with less dependence on the associated heat sink, since the electric efficiency is higher (and the produced heat less) than for other micro-CHPs systems.
FC micro-CHPs are available for producing electricity around the clock every day of the year and can always deliver up to the maximum rated power.

Thanks to the high modulation range, the FC-based micro-CHPs adapt to the users' electrical and thermal needs for residential and small commercial applications. A battery of FC-based micro-CHPs modules, integrated with a central heating system, guarantees higher power generation for small commercial buildings. The small size of the FC-based micro-CHPs, the modulation range and the multiple modular solutions, contribute to an easy management in a smart grid.

In conclusion: The advantages are a demand-driven production, the higher electrical efficiency and less heat production. Furthermore, the devices have a wider range of applications making them very flexible.

Question 6: Where is there greater/smaller potential for micro-CHPs?

Full question: Are there any places where you see a greater/smaller potential for FC-based micro-CHP units in the future electricity grid? (geographical and other..)

The greatest potential is expected to be found in the residential and small commercial applications. Their demand for heat and power are very well suited for the FC-based micro-CHP's dimensions.

One could say that a potential area of application is anywhere where there is a gas grid or gas tank available and the spark-spread is large enough. This could be at or around biogas plants and varying sizes of farms.

From an energetic point of view, there may be a very large potential in the combination of FC micro-CHPs and compression heat pumps. Taking economics into account, the installer's effort and the investments may be too high at the moment to tap this potential.

Question 7: Any additional comments or thoughts.

Full question: Any other comments and thoughts, for example: parameters that are extra important (response time, remote control, economy (export economy), heat storage etc…)

The main concern should be to continue reducing the FC micro-CHP system complexity. It is also important to optimise the systems to grid requirements or aspirations. Right now, the requirements for smart grid functions are not yet clear. There are many ideas, but no specified set of functions that can be developed for integration in the micro-CHP units. There is however some trends this technology is expected to follow.

One such parameter will be the response time of the system. It is important that FC micro-CHPs in smart grids can react (modulate) within 15 minutes since that is the time within which you need to bid on a price on the energy market. While this is within the scope of current technology, one might in the future require the system to be able to modulate within 5 minutes. This will of cause depend on the markets.

Another parameter is data gathering speeds possible for FC micro-CHPs. Current electronics and ICT already achieve real time monitoring. Since this is expensive, metering data is commonly sent every 15 minutes. In general this technology is expensive and steps should be taken to lowering the cost.

Especially regarding the smart grid installations in single and two-family homes, intelligent future electricity grids are necessary. Technical issues still need to be solved in regards to monitoring, aggregation and modulation.

It must be considered that the technologies that will be integrated to a smart grid will be selected by the distribution network operators (DNOs) and transmission system operators (TSOs) according to relative advantage. A closer examination and benchmark vs. other technologies would be relevant.

There is a trend for electrical efficiencies to increase for each generation of the FC micro-CHP technology. The higher electrical efficiencies go, the lesser important heat storage becomes. This will limit the need for and size of hot water tanks in conjunction with the FC micro-CHPs.

In the future there will be more micro-CHPs combined with batteries. This reduces the amount of electricity that the households take from and put into the grid. Otherwise with batteries the grid could get stabilized better, since the electric power of batteries is usually higher than the power of a micro-CHP.

A.2 Utility discussion questions

Aggregation

- Is it possible to reach market bid volumes? If yes, how? If no, why not?
- How many installed units do you need for aggregation to make sense?
    - Is it realistic to reach clusters of that size?
- Are the control options and systems available at the moment sufficient to make virtual power plants feasible?
    - If the answer to the above question is no, what is then needed to make it realisable?
    - What level of expense would it require from your side and would it be enough for you to decide not to support virtual power plants?
- Regarding all the pros and cons, would aggregated FC micro-CHP clusters be of interest to the utilities?

Operation

- Are the start-up times of SOFC systems (hours) a problem in your point of view?
- Is it a requirement for you that systems are operational 24 hours a day?
    - If that is the case, are there currently enough incentives to keep the systems running? (tariffs, degradation mitigation etc.)
- Which operation scheme (combination of operation modes) would you prefer? Is the suggested operation (see answer to question 2) sensible?

Data, metering and control

- Does the current metering and data gathering technology cause any limitations? Especially, is the cost an important factor?
- What security requirements do you believe to be needed for active control over the internet?
- What level of system control would be a requirement? Any control not required that would be desirable?
- Who should have control capabilities? Utilities, end-user, grid operators, manufacturers others?

Economics

- What kind and size of subsidies do you estimate to be needed for market introduction of FC micro-CHPs?
- What level of feed in tariffs would be needed?

Distributed generation

- Will the reduction of transmission losses afforded by in-house generation make a difference at realistic volumes?
    - Would this gain be lost somewhere else due to some aspect of distributed generation?

- At what level will distributed generation affect plans for grid expansion?

General

- Are there any additional considerations forgotten in the above? If anything is overlooked, please include it here.
- Is there anything in the answers from the manufacturers you disagree with strongly?
- What do you perceive as the greatest limiting factor for the introduction of FC micro-CHPs to the market? What can be done to mitigate it?

A.3 Current and previous FC micro-CHP projects

A. 3.1 ene.field

http://enefield.eu/

ene.field is a European fuel cell micro-CHP project running from September 2012 to August 2017. The project aims to deploy up to 1000 residential fuel-cell-based micro combined heat and power (FC micro-CHP) installations, across 12 key member states. It represents a step change in the volume of fuel cell micro-CHP deployment in Europe and a meaningful step towards commercialisation of the technology.

The programme brings together 9 European FC micro-CHP manufacturers into a common analysis framework to deliver trials across all of the available fuel cell CHP technologies. Fuel cell micro-CHP trial units will be installed and actively monitored in dwellings across the range of European domestic heating markets, dwelling types and climatic zones, which will lead to an invaluable dataset on domestic energy consumption and micro-CHP applicability across Europe.

By learning the practicalities of installing and supporting a fleet of fuel cells with real customers, ene.field partners will take the final step before they can begin commercial roll-out. An increase in volume deployment for the manufacturers involved will stimulate cost reduction of the technology by enabling a move from hand-built products towards serial production and tooling.

Table 2 below gives technical characteristics of the systems being deployed within the ene.field project.

Table 2: Technical characteristics of systems deployed within ene.field. * based on the lower heating value, ** PEM = Polymer Electrolyte Membrane Fuel Cells, SOFC = Solid Oxide Fuel Cells, LT = low temperature, HT = high temperature and IT = intermediate temperature [16].

Technical characteristics	Summary table of products	
Fuel cell technology	LT-PEM / HT-PEM **	SOFC / IT-SOFC**
Electrical power	1 – 5 kW	0.8 – 2.5 kW
Thermal power	1.4 – 7.5 kW	1.4 – 25 kW
System efficiency (LHV*)	85 - 90 %	80 - 95 %
Electrical efficiency (LHV*)	35 %	35 - 40 %
System type	Floor	Wall or Floor
Certification	CE	CE

The data produced by ene.field will be used to provide a fact base for FC micro -CHP, including a definitive environmental lifecycle assessment and cost assessment on a total cost of ownership basis.

To inform clear national strategies on micro-CHP within member states, ene.field will establish the macro-economics and CO_2 savings of the technologies in their target markets and make recommendations on the most appropriate policy mechanisms to support the commercialisation of domestic micro-CHP across Europe. Finally, ene.field will assess the socio-economic barriers to

widespread deployment of micro-CHP and disseminate clear position papers and advice for policy makers to encourage further roll out.

Partners: BAXI INNOTECH, Bosch Thermotechnik, British Gas, COGEN Europe, Technical University of Denmark, Dantherm Power, DBI - Gastechnologisches Institut, Dolomiti Energia, DONG Energy, Elcore, Element Energy, Environment Park, European Institute of Energy Research, GDF-SUEZ, GWI - Gas- und Wärme-Institut Essen, HEXIS, HyER, Imperial College of Science, Technology and Medicine, POLITO – Politecnico di Torino, RBZ – Riesaer Brennstoffzellentechnik, SOLIDPower, The Energy Saving Trust, Vaillant, Viessman.

A. 3.2 Danish Micro Combined Heat and Power

http://www.dmkv.dk/english/index_en.html

Danish Micro Combined Heat and Power is a project that ran from March 2006 to December 2014. The project focused on development, testing and demonstration of fuel cell micro combined heat and power units. The aim was to have units ready for Danish and foreign consumers after the end of the project in 2014.

The project was divided into 3 phases: development and laboratory testing of units, limited field test, and field test of a large number of units both natural gas and hydrogen fuelled.

The project was concluded successfully after demonstration of units in private households. The units tested in the project were connected to DONG Energy's Power Hub system and remote control was demonstrated.

Partners: COWI, Danfoss, Dantherm Power, DGC, DONG Energy, SEAS-NVE, SYD ENERGI, Topsoe Fuel Cell.

A. 3.3 Callux

http://www.callux.net/

Callux, started in September 2008, is Germany's biggest practical test for fuel cell heating systems for domestic use. The project aims to demonstrate technical maturity, support further improvements to ensure marketable products, develop supply chains, enhance the product profile of FC micro-CHPs on the market and validate requirements from customers as well as the market.

The project will deploy FC micro-CHPs in consumer households. Here, the units will be tested and demonstrated in real live application. Furthermore, the project will work on development of infrastructure such as standardisation of interface for communication between units and management systems. As of 2014 about 500 fuel cell micro-CHP units had been deployed in the Callux framework.

Partners: BAXI INNOTECH, Hexis, Vaillant, EnBW, E.ON, EWE, MVV Energie, VNG Verbundnetz Gas

A. 3.4 SOFT-PACT

http://www.soft-pact.eu/

SOFT-PACT plans to deploy 80 fuel cell Combined Heat and Power (micro-CHP) systems across a number of EU member states with the assistance of a grant from the Fuel Cell and Hydrogen Joint Undertaking (FCH-JU). The states selected will be based on an EU FC market opportunity study, looking at the properties, services availability and policy and regulation support across the member states to determine the most favourable regions for initial deployment of the fuel-cell-based systems. The field trials will utilise Ceramic Fuel Cell's GENNEX technology.

Learning points expected of the project include optimisation of the fuel cell system specifications and design such as system hot water and heat usage requirements and physical constraints of the integrated FC appliance. Additionally, it is expected that lessons will be learned on barriers to deployment within the selected regions, the skills required for installation engineers, and policy and regulations support needed.

Additionally, the members of the consortium will promote FC knowledge to the general public through product placement, trialist recruitment campaigns and sponsoring and attending conferences.

Partners: FCH-JU, E.ON, Ideal Boilers Limited, CFCL, HOMA Software

A.4 Current and previous smart grid projects

Over the last years, a large number of smart grid projects have been carried out in Europe. These projects focus on various aspects ranging from demonstration down to fundamental details. Below is a small review of projects that are relevant to this position paper. A webpage created by the European electricity association EURELECTRIC and the European Commission's Joint Research Centre (EC JRC), can be used for further information about previous and on-going European projects: https://portal.smartgridsprojects.eu/ [15]

A.4.1 EcoGrid

http://www.eu-ecogrid.net/

EcoGrid is an EU funded smart grid demonstration project aiming to illustrate the feasibility of operating a power system with more than 50% renewable energy sources using modern information and communication technology (ICT). The trials are currently taking place on the Danish island of Bornholm and the aim is to include up to 1900 electricity consumers and up to 100 industrial and commercial buildings.

The project focuses on illuminating consumption flexibility based on market information. The consumers are divided into three groups: a static control group, a manual control group that must respond to market signals manually and an automatic control group. This latter group is again divided into a group where consumption is regulated autonomously based on market signals and a group where consumption is regulated by an aggregator. The demonstration project is set up as a functional but isolated market and the manual and automatic control groups receive real-time market data every 5 minutes. In that way the systems can be demonstrated without interfering with the Nordic power exchange.

Data collected for all the 1900 consumers from October 2014 to February 2015 show that in these cold months of winter a demand response of up to 285 kW was achieved. The total energy shifted in this period was 35 MWh.

The final project report for EcoGrid can be found through the following link:
http://www.eu-ecogrid.net/images/Documents/150917_EcoGrid%20D6.7%20Overall%20evaluation%20and%20conclusion%201.pdf

Partners: Energinet.dk, Sintef, Østkraft, Technical University of Denmark, IBM, Siemens, Elia, Eandis, Tallinn University of Technology, ECN, TNO, edp, tecnalia, Austrian Institute of Technology.

A.4.2 Grid4EU

http://www.grid4eu.eu/

Grid4EU is a smart grid research and demonstration project running from November 2011 to January 2016. It consists of 6 demonstrators (sub projects) each tied to one of 6 distribution system operators (DSOs) and one European country. Each demonstrator will run 4 years. The project aims to test the potential of smart grids in areas such as renewable energy integration, electric vehicle development, grid automation, energy storage, energy efficiency and load reduction. The focus of

the consortium is fostering complementarity between the demonstrators, and on promoting transversal research and sharing results between the different energy distributors involved.

The project aims to study the interplay between a variety of technologies in a smart grid context. These technologies include low and medium voltage network supervision and automation, interactive systems between network operation and electricity customers, demand side management (DSM), storage and Micro Grids.

As the final report is not yet made, the final evaluation of the demonstrators and the interplay between them is not available. A review of the status of the 6 demonstrators is outside the scope of this paper.

Partners: AAB**,** ALSTOM Grid, ARMINES, CEZ Distribuce, a.s., Cisco, Comillas Pontifical University, ORMAZABAL CURRENT, Electricité de France (EDF), eMeter, Enel Distribuzione S.p.A., ERDF, Iberdrola, Itron Inc, The Royal Institute of Technology (Sweden), The Catholic University of Leuven, Landis+Gyr, Grupo Ormazabal, RSE, RWE Deutschland AG (RWE DAG), Telvent Energía, S. A., Selta, Siemens **,** TUD, Vattenfall Eldistribution**,** ZIV.

A.4.3 Power Hub

http://www.twenties-project.eu
https://www.powerhub.dk/

Power Hub was a virtual power plant developed by the Danish utility DONG Energy as a part of the TWENTIES project. The development and demonstration ran from 2010 to 2013. Power Hub is an IT system that allows for the management of small power generators and power consuming units in a smart grid context. The focus was on commercial partners such as small hydro plants, industrial combined heat and power plants and pumps in water treatment. The task of the system was to optimise and balance the system. The project was demonstrated on commercial terms and 47 owners of distributed energy resources (DERs) joined the demonstration.

When the project ended it was concluded that Power Hub had delivered real economic value for the DER owners, especially through optimisation based on price forecasts and automating relevant operations. Value was also created through ancillary services. The project also demonstrated that Power Hub was capable of delivering services such as reactive power and fast frequency demand response.

Of notable challenges were mentioned attracting and integrating industrial units to participate in a virtual power plant. A second large challenge was scaling up the virtual power plant on commercial terms due to Danish regulatory regime and market design.

A.4.4 Integris

http://fp7integris.eu

The Integris project was a smart grid project, running from March 2010 to September 2012, with the task of developing an all-encompassing ICT infrastructure. This was to include monitoring, operation,

customer integration, voltage control, quality of service control, control of distributed rnergy resources and asset management to improved power system operations.

The project partners state that the future of electric system comes from the construction of an adaptive, optimized, integrated and distributed intelligent distribution network, interactive with consumers and markets. Thus the project aims to define and develop an integrated ICT environment able to efficiently encompass the communications requirements that can be foreseen for smart grids. Of special concern is power line communication and wireless communication. This infrastructure should be secure, flexible and low-cost.

Partners: a2a, Current Technologies International, DS2, Endesa Network Factory, laSalle, Ilight, Indra Sistemas, Schneider Electric, Tampere University of Technology.

A.5 Glossary

CHP	Combined Heat and Power
EC	European Commission
FC	Fuel Cell
FiT	Feed in tariff
HT	High temperature
IT	Intermediate temperature
kW	kilo Watt
LHV	Lower heating value
LT	Low temperature
PEM	Polymer electrolyte membrane fuel cell
SOFC	Solid oxide fuel cell

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